Stochastic cumulus clouds based on fields from a large-eddy simulation

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Research goal

To investigate the degree to which anisotropy in cumulus cloud fields affects shortwave radiative transfer and the mechanisms by which this occurs.

Rationale:

- Detailed 3D cloud measurements are unavailable.
- Cloud structure is often assumed isotropic, even though anisotropic clouds occur frequently.

Types of anisotropy

Stretching

(Landsat Thematic Mapper, July 7,1999)

Tilt

(Karlsruhe Wolkenatlas)

Advantages of stochastic fields vs. LES scenes

- Anisotropy in scenes can be precisely controlled.
- Anisotropy can be adjusted *while basic cloud properties are maintained*.
- A statistically significant number of similar scenes can be easily generated.

Test scenes

Cloud scenes generated using the Evans and Wiscombe stochastic field generation program.

Input: Statistics of 12 LES cumulus cloud scenes

Output: Ensemble of 20 3D LWC distributions

For each member of the ensemble, create two series of fields in which

* tilt increases
* horizontal anisotropy increases

while the liquid water content distribution and cloud fraction in each level and the correlation between the levels remain fixed.

Evans and Wiscombe stochastic field generation algorithm

Similarities to Fourier (power spectrum) method:

- Represents desired cloud structure via orthogonal function decomposition.
- Creates fields by multiplying orthogonal component amplitudes by Gaussian random deviates and transforming back to real domain.
- Output fields are isotropic.

[Evans and Wiscombe, Atmospheric Research, 72:263-289 (2004)]

Differences from Fourier method: Inputs

- Uses power spectra of an ensemble of sample fields rather than assumed power law for horizontal structure.
- Vertical structure also based on input field statistics.
  - Generally different than horizontal structure.
  - Described by cross-correlation matrix of binary cloud fields at all heights.
  - Decomposition by empirical orthogonal functions.

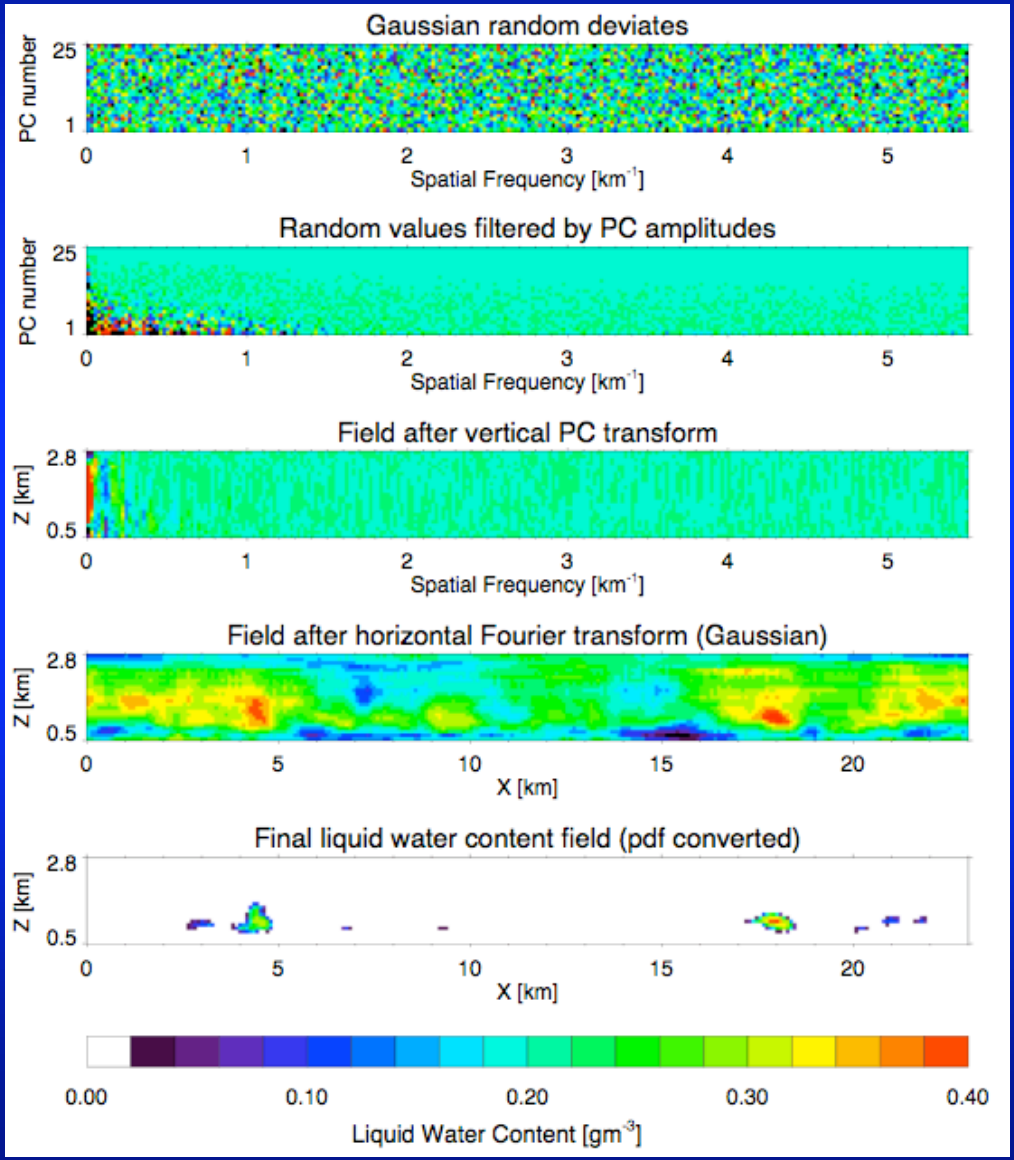
Differences from Fourier method: Output

- Creates 2- or 3-dimensional fields from 2D (x-z) input.
- Statistics over ensemble of output fields closely match desired values.
- Gaussian values in generated fields are mapped to LWC pdfs of input field ensemble.
- Can generate a correlated effective radius field for every output LWC field.

Evans and Wiscombe algorithm: Synopsis

- Compute average cross correlation function for all height pairs in binary versions of input fields.
- Find equivalent “Gaussian” correlation matrix.
- Convert “Gaussian” correlation matrix into frequency domain representation via Fourier transform.
- Perform Eigenvalue decomposition on each Fourier term (i.e., at each spatial frequency).
- Generate field of Gaussian random deviates.
- Multiply random field by filtering amplitudes (square roots of Eigenvalues).
- Transform resulting field back to real space via principal component and Fourier transforms.
- Convert Gaussian values to LWCs using input PDFs.

Stochastic field generation via Evans and Wiscombe algorithm



Modifications to Evans and Wiscombe algorithm

- Uses 3D fields as input
  - Liquid water content fields from large-eddy simulations
- Output fields are anisotropic
  - Type and degree of anisotropy specified by user

Accommodation of 3D input

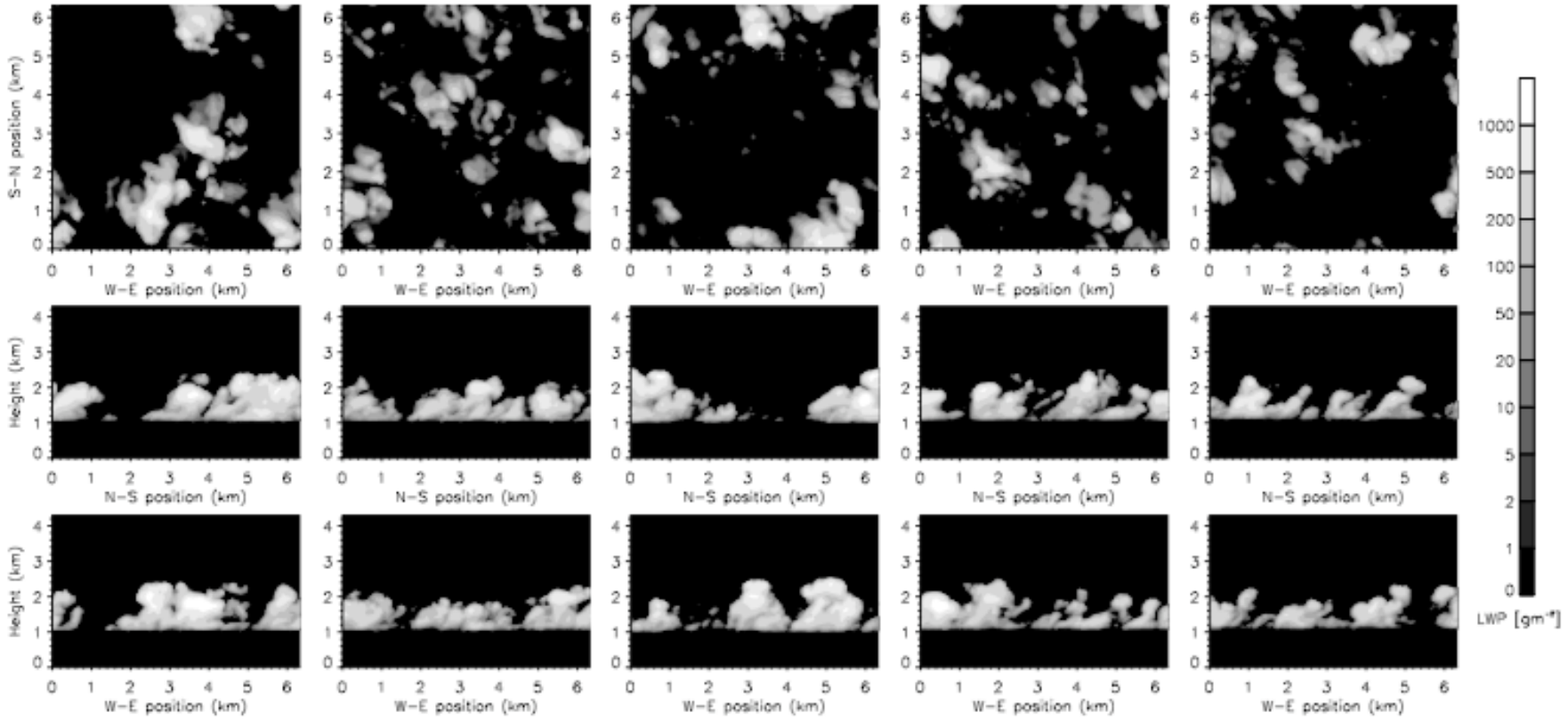
Input statistics:

Compute 2D correlation functions between height pairs.
Integrate radially to obtain mean 1D correlation functions.

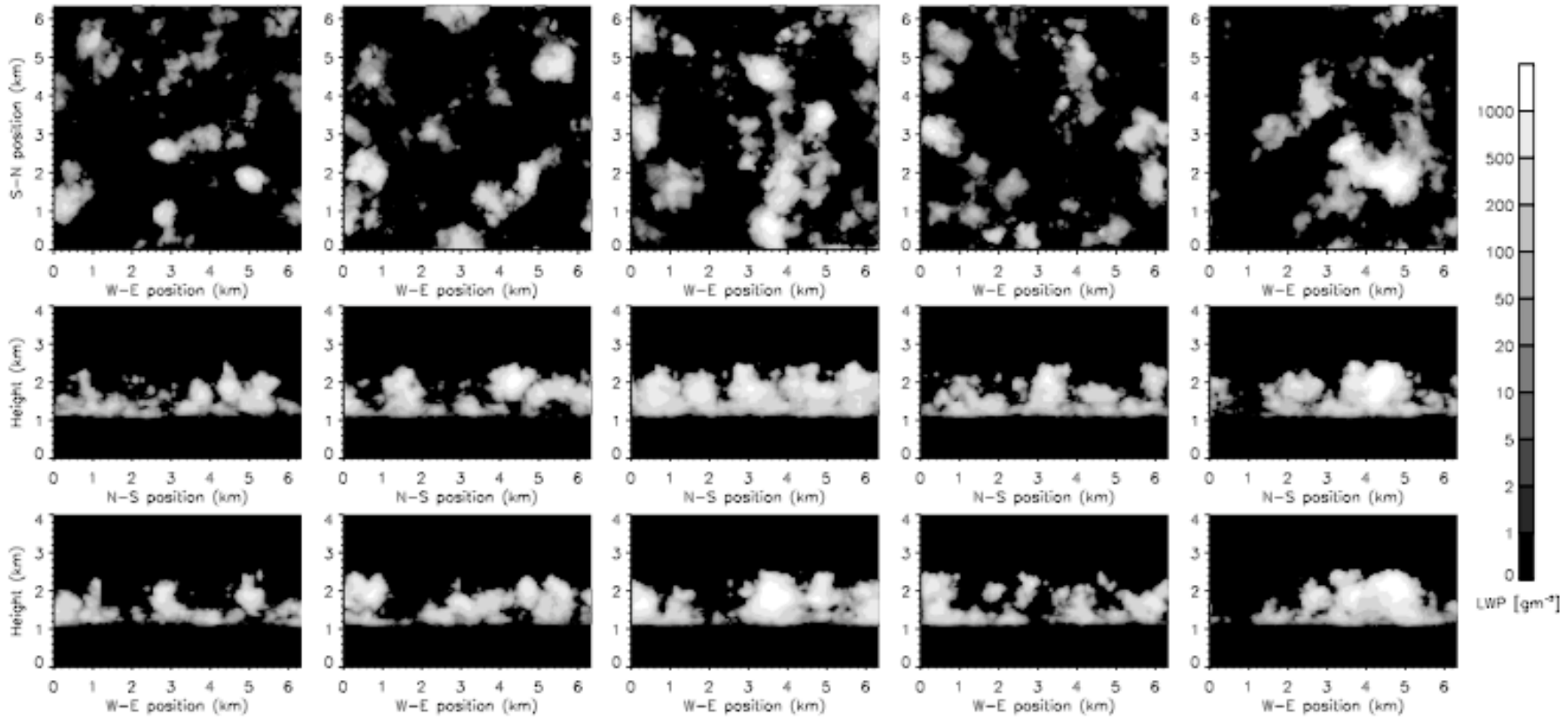
Output field generation:

Use regular 3D field technique, but no spectral optimization is required.

Example input scenes



Example isotropic output scenes



Incorporation of tilt

Displace each vertical level horizontally.

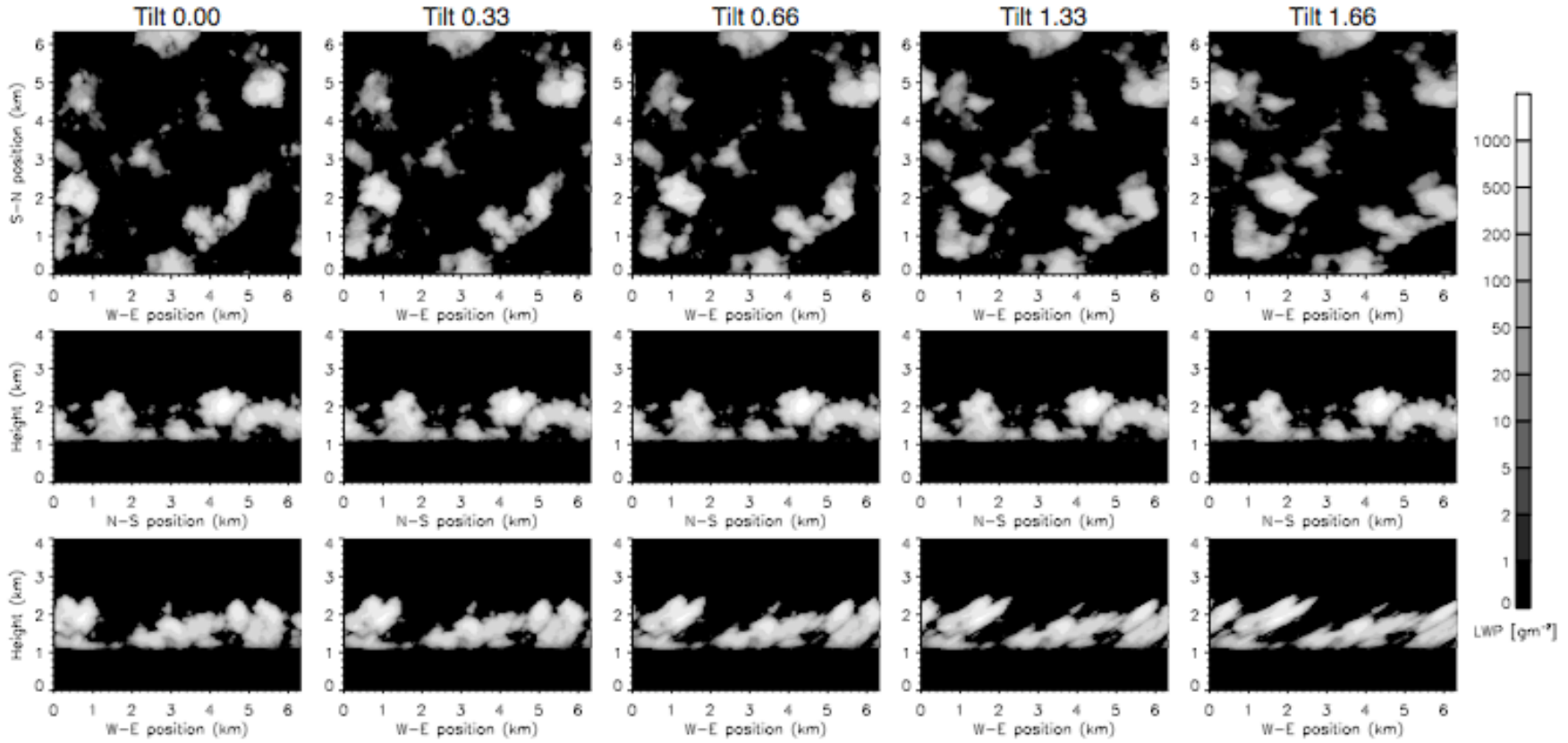
Operation performed in Fourier space by applying vertically increasing phase shift:

$$d\theta = e^{(k_x/c_x)\, F_t n_z\, \pi i}$$

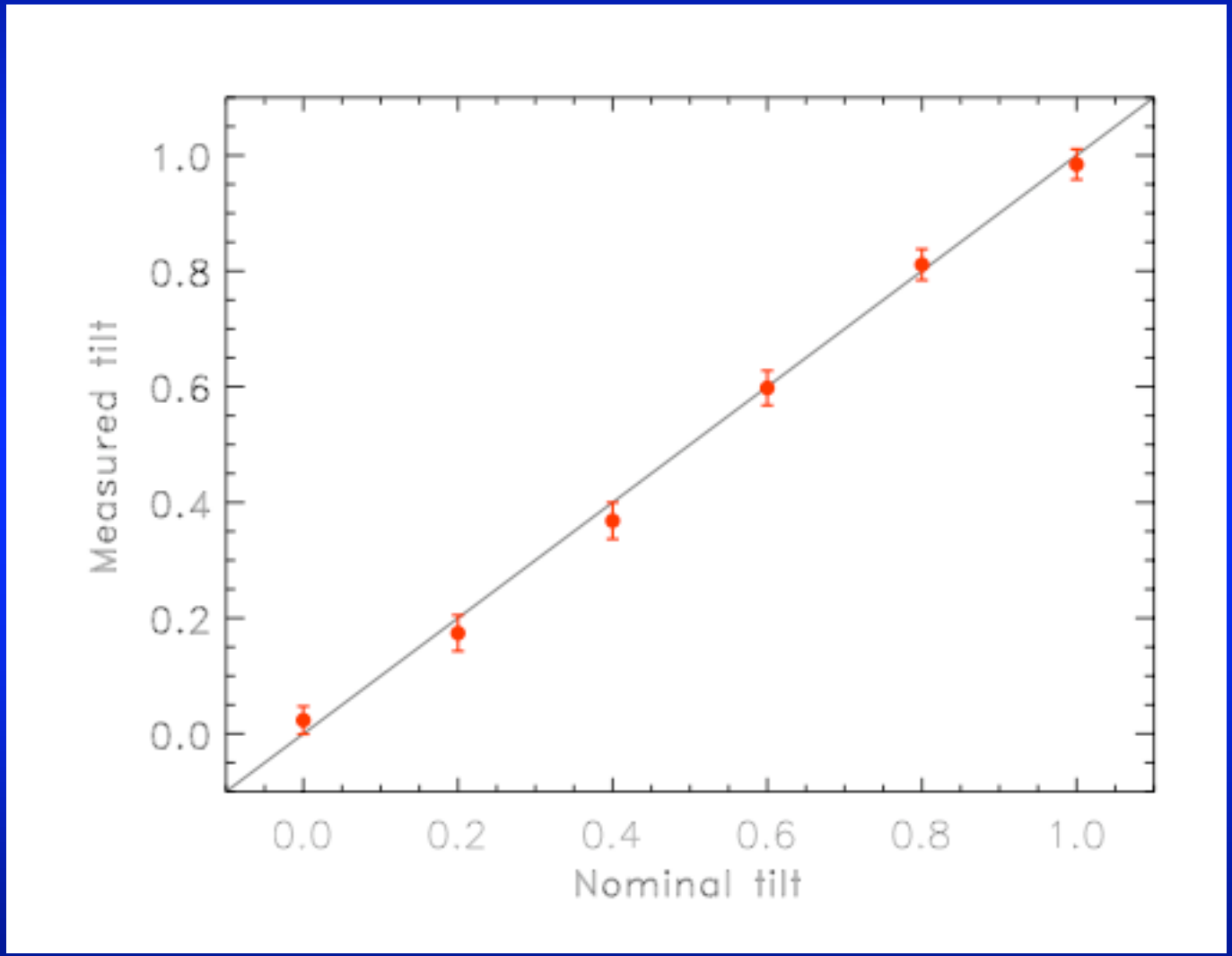
where

k_x = horizontal spatial frequency index
c_x = 1/2 number of FFT frequencies
n_z = vertical index
F_t = tilt parameter in lags/level

Example output fields: Tilt



Tilt control



Incorporation of horizontal anisotropy

During field generation, elongate horizontal power spectra in N-S direction and compact in E-W direction.

When assigning Eigenvector values in the 3D array, instead of using the Eigenvector for (radial) spatial frequency index

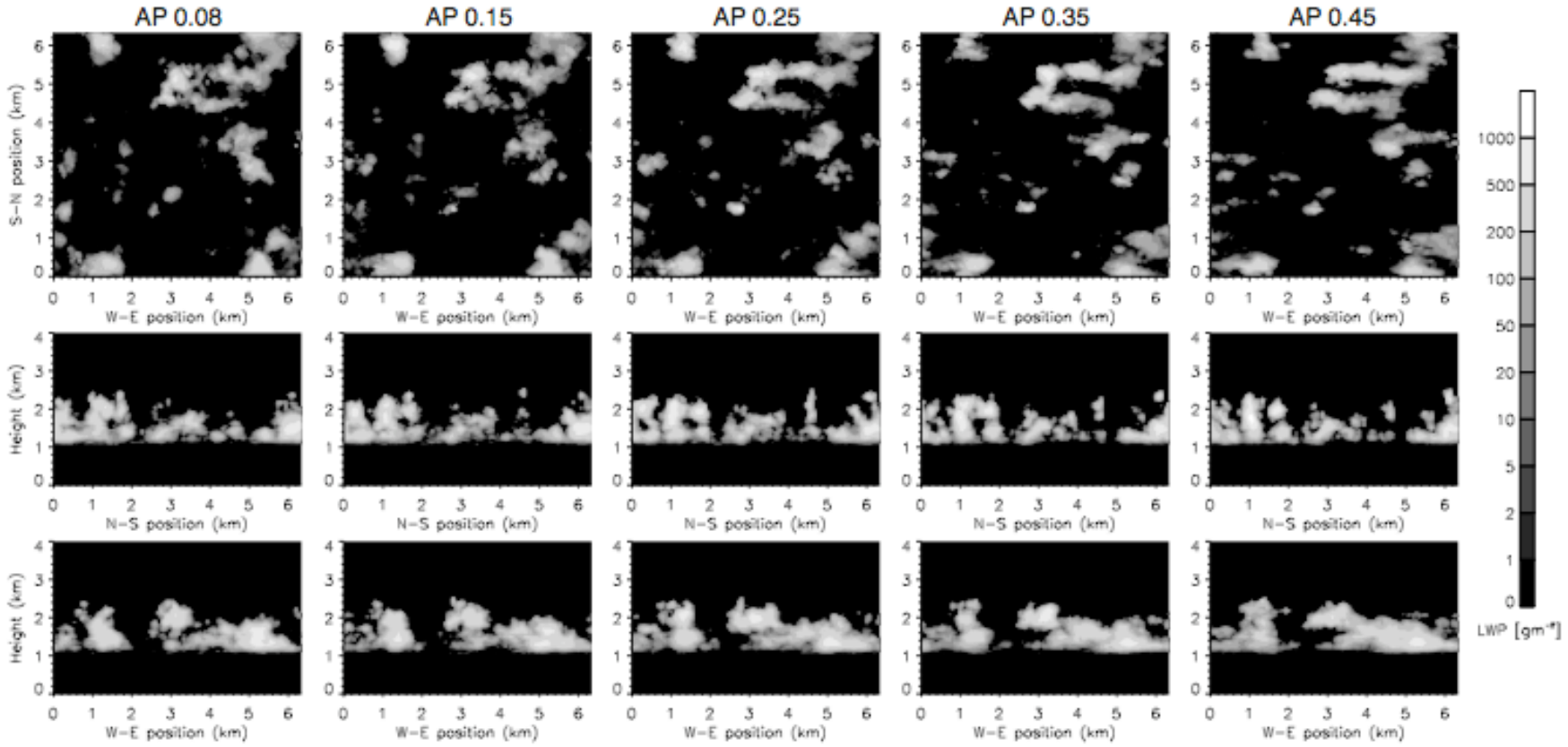
$$k_r = \sqrt{k_x^2 + k_y^2}$$

substitute the vector for

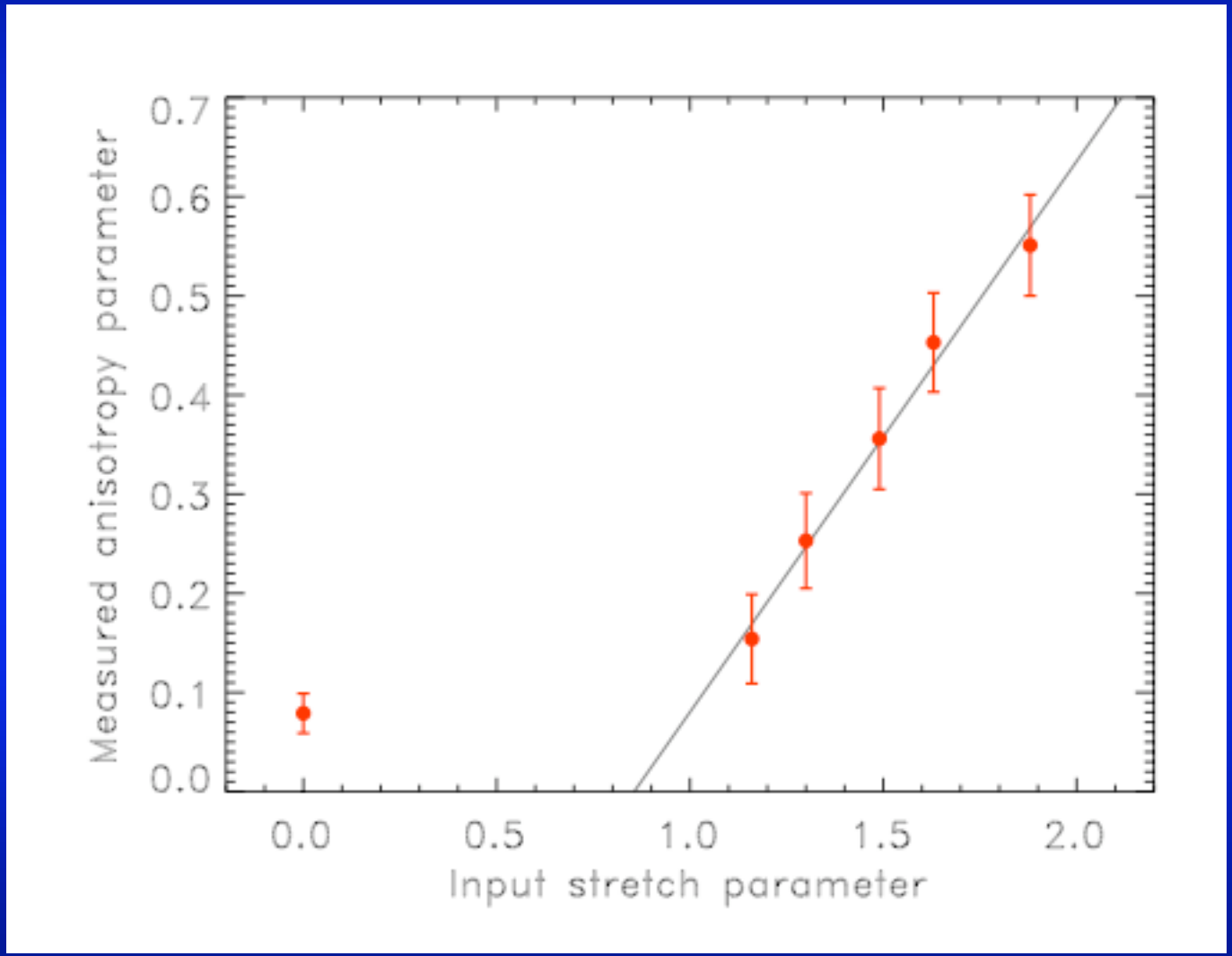
$$k_r = \sqrt{(F_s\, k_x)^2 + (k_y/F_s)^2}$$

where F_s is the stretching parameter.

Example output fields: Stretch

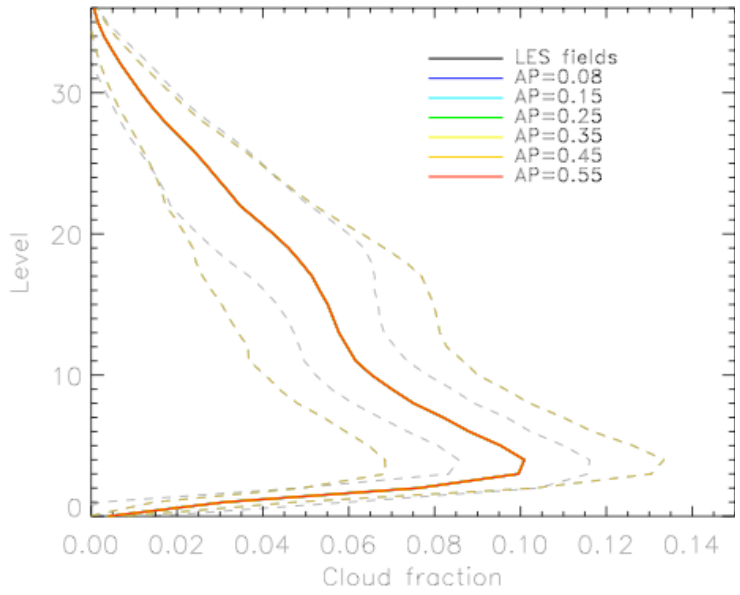


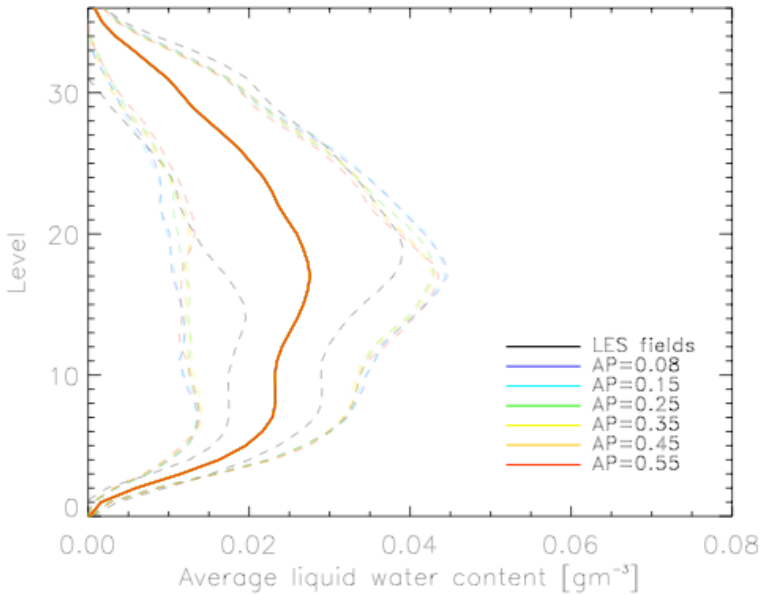
Stretch control



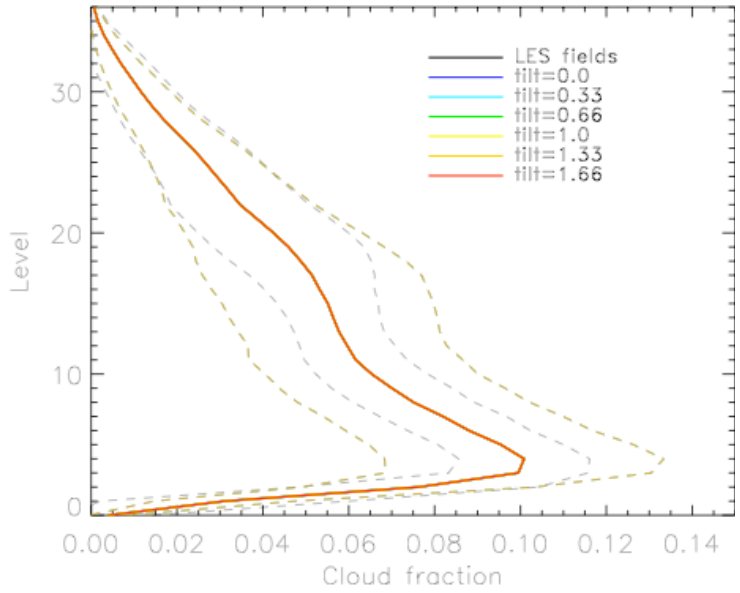
Cloud fraction

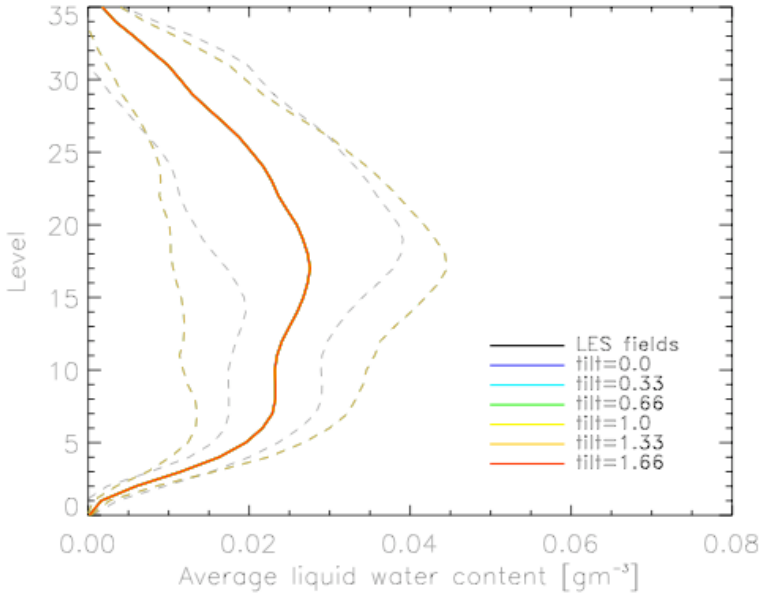
Liquid water content





Stretch

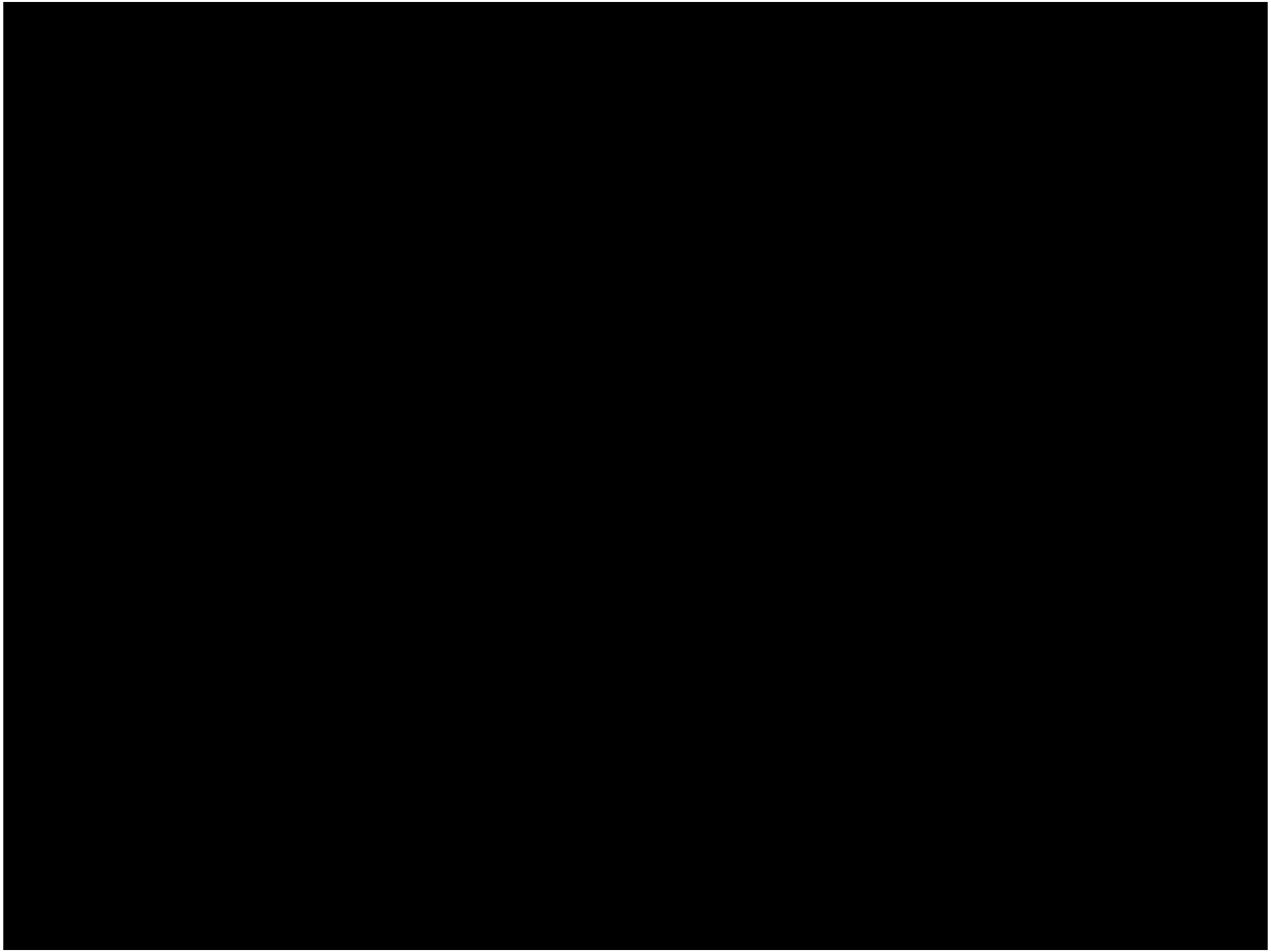




Tilt

Conclusions

- A modified version of the Evans and Wiscombe stochastic field generation model has been used to construct anisotropic LWC fields based on cumulus scenes from large-eddy simulation.
- Inclusion of arbitrary degrees of both tilt and horizontal anisotropy has been demonstrated.
- Radiatively important cloud properties remain constant as anisotropy is changed.



Types of Anisotropy

1) Stretching (horizontal anisotropy):

- Elongation of individual cells or linear arrangement of cells
- Measured via anisotropy parameter (AP):

  isotropic 0 <= AP <= 1 linear

2) Tilt (vertical anisotropy):

- Horizontal displacement with height
- Measured in m/m (slope)

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- Horizontal displacement with height
- Measured in m/m (slope)

(Karlsruhe Wolkenatlas)

Evans and Wiscombe (2004) stochastic field generation algorithm

Similarities to Fourier (power spectrum) method:

- Represents basic cloud structure in terms of orthogonal functions
- Creates fields by multiplying orthogonal components by Gaussian random deviates and converting back to real domain
- Output fields are horizontally isotropic

Differences:

- Uses mean power spectrum of sample fields for horizontal structure
- Vertical structure also based on input field statistics
  - Described by cross-correlation matrix of binary cloud fields at all heights
  - Decomposition by empirical orthogonal functions
  - Generally different than horizontal structure
- Generated field values are mapped to mean LWC pdfs of input fields
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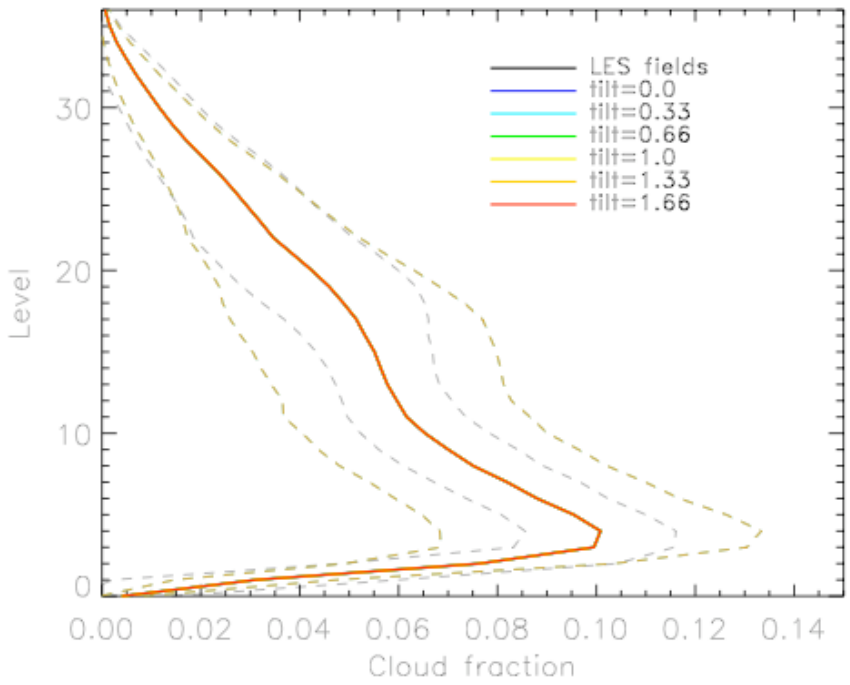
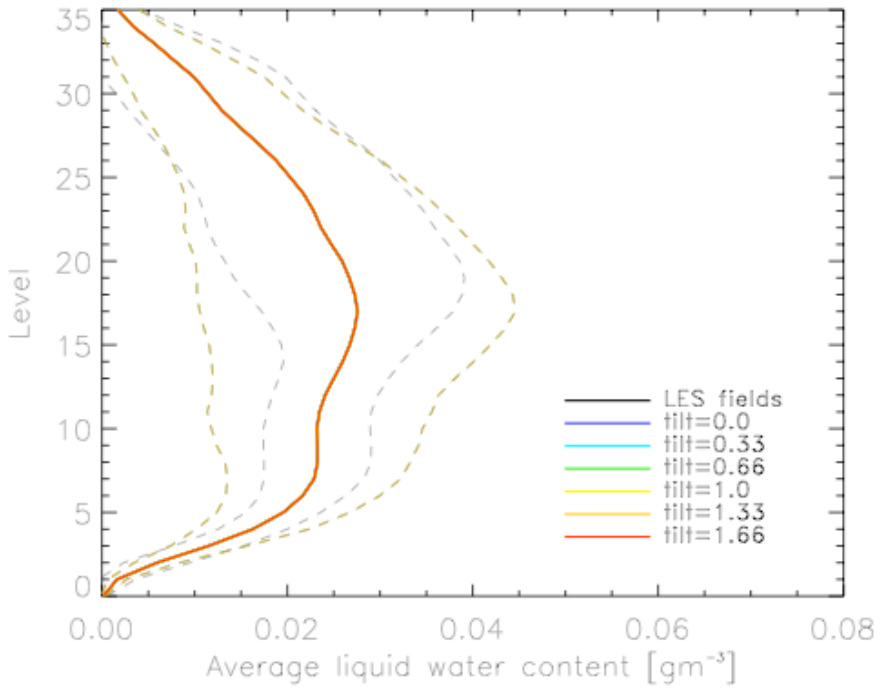
Output cloud field properties: Tilted fields

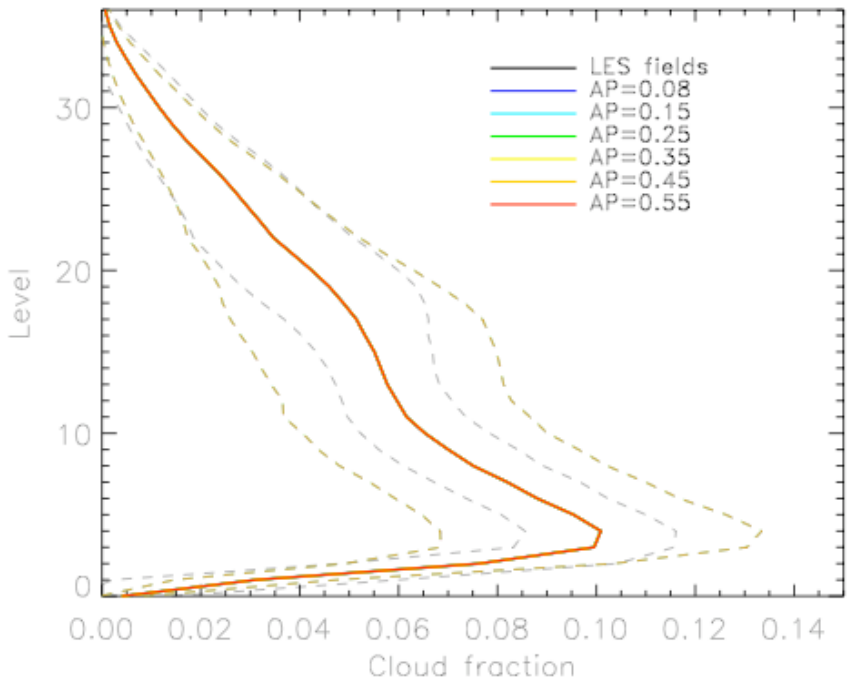


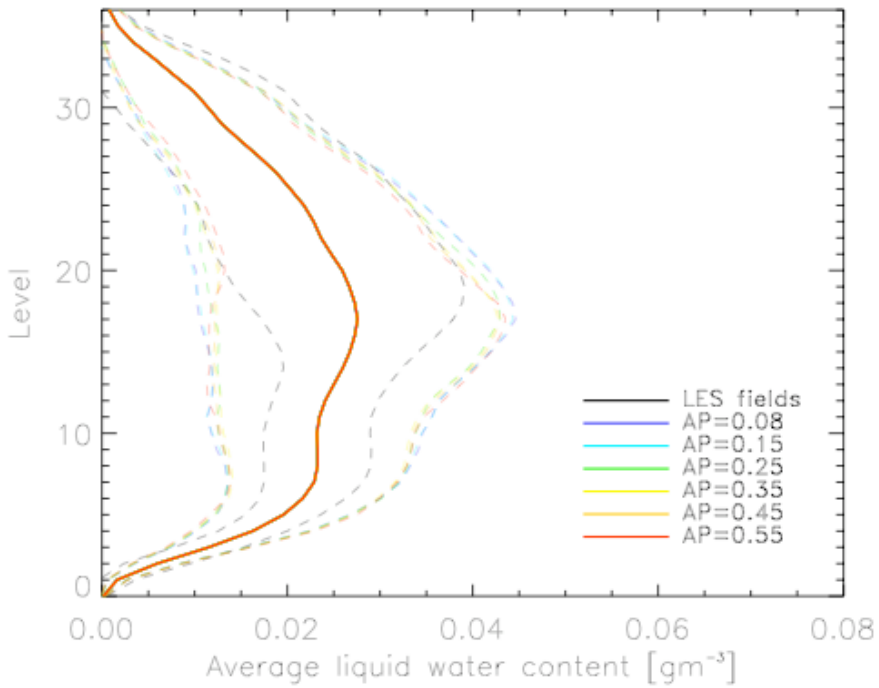


Cloud fraction

Liquid water content

Output cloud field properties: Stretched fields





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Method

Perform Monte Carlo radiative transfer calculations on series of cloud scenes with increasing anisotropy.

Compare results of full 3D computations to IPA and TIPA results.

$\Rightarrow$ Need cumulus scenes with varying degrees of anisotropy.